§2. Significant Stabilization of Ideal MHD Instabilities by the Boundary Modulation in Heliotrons

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The boundary modulation induced by the free boundary motioin of MHD equilibrium mainly appears as a large Shafranov shift of the whole plasma. Thus, it might be expected that the MHD stability is improved by the boundary modulation. Figure 1 shows the comparison of global mode stability analyses between fixed (the first and the second columns) and free (the third and the fourth columns) boundary currentless MHD equilibria with $\beta = 3\%$ for three different plasma-vacuum boundaries denoted by ι_v in the inward-shifted LHD configuration. The pressure profile is assumed to be $P(s) = P(0)(1-s)(1-s^9)$ with the normalized toroidal flux s. This pressure profile is considered to be similar to that in experiments.

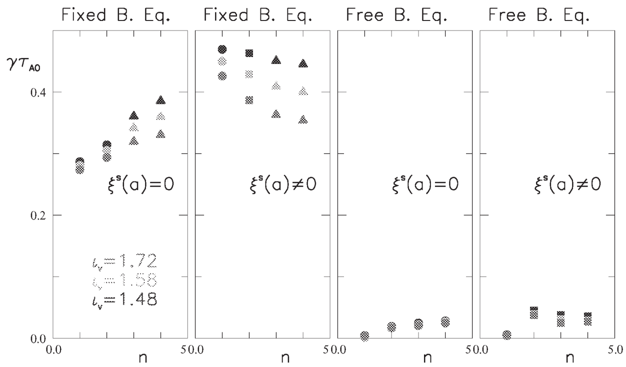

FIG. 1: Normalized growth rate $\gamma\tau_{A0}$ vs toroidal mode number n for MHD equilibria ($\beta = 3\%$) with fixed boundary (the first and the second columns) and with free boundary (the third and the fourth columns). Global mode stability analyses are performed for fixed boundary condition with $\xi^s(a) = 0$ (the first and the third columns) and for free boundary condition with $\xi^s(a) \neq 0$ (the second and the fourth columns). Blue, green, and red colors correspond to the MHD equilibria with the vacuum rotational transform at the plasma boundary being $\iota_v = 1.48$, $\iota_v = 1.58$, and $\iota_v = 1.72$, respectively. Circles (triangles) denote interchange (tokamak-like ballooning) modes. The squares indicate the ballooning-like structure induced by the free boundary motion with $\xi^s(a) \neq 0$.

The global mode stability analyses are performed for fixed boundary condition with $\xi^s(a) = 0$ (the first and the third columns) and free boundary condition with $\xi^s(a) \neq 0$ (the second and the fourth columns), where the growth rates of the most unstable modes normalized by the Alfvén transit time on the magnetic axis $\gamma\tau_{A0}$ are drawn with respect to the toroidal mode number n, where $\tau \equiv \sqrt{\mu_0\rho_m}/(2\pi\iota)dV/d\Phi_T$ with the toroidal flux Φ_T and the permeability in the vacuum μ_0. For typical high-β LHD operation parameters with the field strength $B \sim 0.5$T and proton density $n_e \sim 3\times10^{19}\mathrm{m}^{-3}$, $\gamma\tau_{A0} = 0.1$ corresponds to around 40μsec. It is very clear that the siginificant MHD stabilization is brought by the boundary modulation induced by the free boundary equilibria.

The β-dependences of the growth rates of the free boundary perturbations $\xi^s(a) \neq 0$ are shown in Fig. 2 for 4 mode families, in three free boundary MHD equilibria with different vacuum boundary. For $\beta < 3\%$, the behavior of the growth rates of free boundary perturbations with respect to β value are similar to those of the fixed boundary perturbations. All the most unstable modes are interchange modes, and the normalized growth rates $\gamma\tau_{A0}$ decrease as β increases independent of plasma vacuum boundary reflecting the change of the rotational transform ι and the improvement of the Mercier criterion D_I induced by the boundary modulation. The significant stabilizing effects are produced by the boundary modulation as β increases.

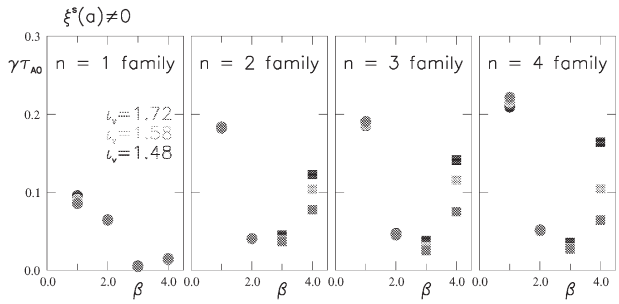

FIG. 2: β-dependences of the growth rates for 4 mode families under the free boundary stability condition with $\xi^s(a) \neq 0$. Blue, green, and red symbols correspond to free boundary MHD equilibria with $\iota_v = 1.48$, $\iota_v = 1.58$, and $\iota_v = 1.72$, respectively. Circles (squares) indicate interchange (free boundary induced ballooning) modes.

[1] Nakajima.N,*et al.*,in Fusion Energy 2004 (Proc. 20th Int.Conf.Vilamoura,2004)IAEA,Vienna,TH/6.